

Report of the Two-Station Doppler (VLBI) Demonstration Conducted With Mariner 9

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The Mariner 9 spacecraft was simultaneously tracked by the Echo Deep Space Station in the Goldstone Deep Space Communications Complex and Woomera Deep Space Station (no longer operational) during the month and a half prior to Mars encounter. The doppler data obtained were generated using hydrogen masers in the Frequency and Timing System. The benefits gained by tracking with two stations simultaneously and the difficulties encountered in processing the data are described. The results indicate that it is necessary to difference the two-way and three-way doppler explicitly if batch filtering is to be employed when there is significant process noise related to the spacecraft. The results, though promising, are not as conclusive as might be hoped for due to the limited amount of data.

I. Introduction

Analysis and simulations have shown that orbit determination for a spacecraft with process noise, e.g., unmodeled nongravitational forces, can be greatly enhanced by simultaneously obtaining doppler from two remote stations. These simulations are described in Ref. 1 and also described in the second section of this article.

To demonstrate the validity of these assertions, an experiment was undertaken with the Mariner 9 spacecraft. Hydrogen masers had been installed and were operational at two deep space stations—Echo (DSS 12) at Goldstone DSCC and DSS 41 at Woomera, Australia.¹ These hydrogen masers, provided by the Goddard Space Flight Center (GSFC), offered an excellent opportunity to demonstrate two-station doppler. The California-Australia baseline was quite well suited for this demonstration, since an overlap (mutual view period) of 4 hours was available for Mariner 9 during the latter part of the cruise phase.

¹No longer operational.

In addition to the special equipment at the two stations, the experiment could also take advantage of an unusually high level of nitrogen gas leakage from the spacecraft attitude-control subsystem. The leakage (shown in Fig. 1) could not be perfectly modeled, and represented the type of process noise that two-station tracking is intended to overcome.

Consequently, permission was obtained to extend the coverage by DSSs 12 and 41 to track throughout their mutual view period on 18 days during the period October 4 to November 14, 1971. The demonstration had to be performed before the spacecraft went into orbit around the planet Mars since after Mars orbit insertion, the acceleration of the spacecraft by Mars would mask any process noise effect.

The DSN was requested to perform the handover (re-assignment of transmitters) at the center of the overlap. By this tracking pattern, equal amounts of three-way data could be obtained from both stations. During the demon-

stration, this request could not always be met since the Mariner Mars 1971 (MM'71) Project required that DSS 12 transmit all the way to the end of the view period, so that commands could be entered into the spacecraft from Goldstone. Consequently, only four handovers were executed in the center of the overlap, which proved very unfortunate, as will be discussed later.

II. Description of the Experiment

The two-station doppler demonstration had as its original objectives:

- (1) To demonstrate that three-way data can be processed by the tracking system and orbit determination programs.
- (2) To demonstrate that two-way and three-way doppler can be used to overcome the process noise problem in spacecraft navigation.
- (3) To evaluate the merits of explicitly differencing two-way and three-way doppler as opposed to merely using the two data types together.

The Mariner 9 spacecraft experienced fairly high gas leakage¹ for a Mariner class spacecraft, as shown in Fig. 1. The MM'71 Navigation Team had overcome this problem, and was successful in this effort, by using telemetry data to correct the trajectory to compensate for the gas leakage. Although there was some uncertainty in the magnitude of the leaks, their time of occurrence was quite well known from the spacecraft telemetry.

In the initial stages of data analysis, the Orbit Determination Program (ODP) was used with a trajectory which had been corrected for gas leakage. The F2-only solutions (using only two-way doppler) were so close to the Project's current best estimate that there was little hope of improvement when three-way data were added. Consequently, a trajectory which ignored the gas leakage was used, so that improvements by employing two-station doppler could show their potential advantage if the gas leakage was not detected, or if the magnitude of the leakage was very uncertain.

The long arc solution designated by the Project as its best estimate was employed as a standard of comparison for all target plane results determined by this experiment. Station location solutions were compared to the DSN station location work performed after the Mariner 9 Mission since these are the current best estimates of these parameters.

¹Accelerations due to gas leaks are usually $< 10^{12}$ km/sec².

The accuracy or reasonableness of other parameters was based on discussions with experts in each particular field.

In the case of the clock frequency offset, the discussions with S. Ward and F. Borncamp of Division 33 indicated that the biases which result from the difference in frequency between the two clocks should be less than 10 mHz. In addition to this, it was known that the bias should be equal in magnitude but opposite in sign on each side of a handover—i.e., when the transmitter assignment is changed from one station to the other.

A third measure of acceptability of experimental results for the frequency bias was to compare the value obtained when the bias was estimated by the ODP with the average of the three-way minus two-way residuals when three-way data were not in the solution. As discussed in later sections, all three criteria have some inherent problems.

Table 1 and Fig. 2 show the data used. These data include two-way doppler (F2), three-way doppler (F3), their difference (F3-2), and discrete spectrum range (Mu). Although the two-way data were available through most of the view period, they were restricted to a short interval near meridian transit for each station, and the mutual view period.

The one-minute F2 and F3 data obtained were compressed up to 10 minutes and synchronized to maximize the number of usable points.

As shown by Table 1 and Fig. 2, there were not as many three-way data obtained as had been hoped for. There are actually only about six days in which the overlap is well covered, and only four of these have the handover near the middle of the overlap. In addition to the doppler data, there are Mu-ranging points fairly evenly distributed throughout the arc. These proved very valuable.

III. Discussion of Solutions

The analysis was all performed postflight. Test philosophy was to process the data as though ignorant of any gas leaks and to compare results using various combinations of four data types (two-way doppler (F2), 3-way doppler (F3), their difference (F3-2) and discrete spectrum range (Mu)). It was assumed that some F2 and Mu data would be needed to establish the geocentric orbit, but a method had to be found to weight the data to give only as much geocentric information as necessary without falling prey to the process noise present in these data.

The more important difficulties occurred in trying to eliminate the three-way frequency biases and transmission media effects.

Even though the expected three-way biases using the hydrogen masers were only about 5 mHz, they had a significant effect on target plane results and had to be removed. Analysis of the instrument calibration data showed that the uncertainty in the determination of the clock drifts (which cause the biases) was much larger than the magnitude of the drifts themselves (Fig. 3), which seemed to indicate those independent measurements could not be used to model the biases. The only recourse was to estimate the biases in the ODP. There were some constraints that could be applied. However, the exceptional stability of the masers would suggest slowly varying biases, if any, although short period changes might be induced from other portions of the tracking system, like the synthesizer. The biases were assumed constant over any pass from a given station and in some solutions, constant over the entire 45-day arc.

It was also found necessary to develop some criteria for judging the quality of the results, because they showed the typical intermediate arc dispersions of 100-200 km in $\mathbf{B} \cdot \mathbf{R}$ (the component in the target plane parallel to the ecliptic).

We established the following criteria for judging the credibility of the bias values obtained from the ODP solution:

- (1) The biases should be invariant with data weight and parameter set.
- (2) The biases should be less than 0.01 Hz and fairly constant over the 45-day span.

IV. Solutions for Frequency Bias

Early attempts at fitting two-way and three-way doppler with partials for the frequency bias resulted in values which did not meet any of the two criteria listed in the above paragraph. These first attempts used partials which modeled the frequency offset as a constant for each station for each day. Realizing that this most obvious approach was not working, a simulation was attempted to investigate the problem.

This simulation consisted of replacing all the two-way residuals with zero and all the three-way residuals with the value 3 mHz. When a solution was attempted with this simulated data, erroneous values resulted, even

though the data were "perfect" and the model was a perfect description of the data. On certain days, the value obtained from the solution for the bias was as far off as 0.5 mHz.

The covariance matrices from these solutions showed that the position of the spacecraft was highly correlated (correlation of X and $Z \sim 0.9$ correlation of Y and $Z \sim 0.98$). To overcome this singularity in position, ranging data were entered and with the addition of this data type, the simulated bias could be solved for with very good accuracy.

When ranging data were used to solve for the three-way frequency bias with real data, the values for the biases which resulted still did not fill the two criteria mentioned earlier. Consequently, other approaches were tried. These consisted of adding off diagonal terms to the *a priori* covariance matrix to model the correlation of the bias from day to day. In addition to these aids, the negative correlation between the three-way frequency bias at the two stations at the time of handover was also modeled by making the partial for the three-way bias one parameter for the two stations with a value of +1 for DSS 12 and -1 for DSS 41. Finally solutions were attempted with a single bias over the entire 45-day period.

Even with all these crutches, the values of the biases were still not consistent from two-way and three-way doppler as compared to differenced doppler. These results are shown in Fig. 4a.

The two requirements for reasonable answers are nearly met by those solutions with F3-2 which solve for differenced station locations rather than one station and the baseline position. These values agree quite well with the difference between the two-way and three-way residuals when the three-way data are not in the solution.

Since the data have been calibrated for the troposphere and ionosphere, it is not believed to be due to this atmospheric effect. The errors in this calibration could cause some of the scatter shown in Fig. 4 on the values obtained for the biases.

Finally, solutions were attempted solving for a single bias over the entire 45-day arc. The bias was arbitrarily assigned a partial of +1 for DSS 12 and -1 for DSS 41. Figures 4a and 4b show the resultant values of the bias and the target plane results. Solutions employing F2 and F3 agree fairly well with differenced doppler solutions solving for differenced station locations in terms of the values of the bias. These results for the bias also tend to

agree with solutions for individual (by pass) biases. However, the effect on station locations and target plane results do not agree.

Even more disturbing is the result obtained when we solve for one bias, one station location (DSS 12) and the baseline. The result for the bias in this case has a sign different from most other solutions.

This is due to the limited data set. In this solution the F2 data from DSS 41 are ignored since they could not be employed to solve for DSS 41's location. Solving for the locations of DSS 12 and DSS 41 as well as the baseline would have been solving for six parameters only four of which are independent.

V. Two-Way Data Only

Two different nominal trajectories, with and without gas leakage corrections were used to process the F2 data described earlier, giving the results shown in Fig. 5. The solutions based on the trajectory with gas leakage corrections (Case A to G) agreed better with the Project's current best estimate (CBE), than the other set (Case A' to G') ignoring gas leakage, and were not particularly sensitive to the inclusion of various parameters except solar pressure. Two-way solutions without gas leakage calibrations spread out perpendicular to the **B** vector bear out the predicted sensitivity of station location and solar pressure solutions to gas leakage when only F2 data are present.

When all the DSS 12 and DSS 41 F2 data between Oct. 4 and Nov. 13 (2600 points) were included the results based on the trajectory without leaks improved somewhat, but the solutions involving station locations, solar pressure and mass (GM) of the moon were still quite volatile. The station longitude corrections from Case G of this set were 2 to 3 m more than the usual 6 m seen in all the other conventional processing and when GM of the moon was not included in the solution the longitude corrections became as large as 18 m.

The sigma used for weighting all the F2 data was 0.045 Hz per 60-s count time. The results of the truncated arc of F2 data processed without gas leakage correction were chosen as a reference for later comparisons because

- (1) It involved the same number of passes as were available for the F2 and F3 data.
- (2) It gave reasonable solutions for the various estimated parameters.

- (3) The absence of gas leak corrections gave the differenced data an opportunity to show the potential improvement for unmodeled accelerations.

VI. Two-way Doppler and Range

When 14-Mu ranging points ($\sigma = 150$ m) were included with the truncated F2 data, the **B**•**T** components of the errors were all decreased by 50 km, bringing them into closer agreement with the CBE (Fig. 6). Although the longitude at each station changed 2m from the F2-only solutions (Fig. 7) no other parameters changed significantly. The spread of these results in the target plane (B-plane) indicates that solutions involving station locations and GM of the moon are still seeing the gas leakage but that the solar pressure parameters no longer are as important, since certain components of the position of the spacecraft are tied tightly down by range data.

VII. Two-way Doppler, Three-way Doppler, and Range

Once F3 points were included, the frequency offset between the two station clocks had to be estimated.

A total of 28 bias parameters representing the frequency offset at each station on each day were added to the "solve for" sets A-G. The results for the biases were discouraging because they varied with changes in data weight and solve for parameters, and were not slowly varying as anticipated. The bias parameters were absorbing not only the frequency offset, but also all the effects due to process noise (gas leakage) and uncalibrated transmission media effects. Unfortunately there was no way to separate these phenomena. The values of B-plane and station location solutions are not significantly different from those of two-way doppler and range (Figs. 6, 7, and 8).

VIII. Differenced Doppler Alone

Differencing F2 from F3 data gave significantly better residuals than either data type taken separately. Figure 9 shows the residuals of F2, F3 and F3-2 during two relatively noisy passes on October 23, 24, 28 and 29 and clearly indicates that the noise of unknown source which is common to both F2 and F3 data has been removed during the differencing. The squares represent the residuals of F3 before the fit and the circles and triangles show the residuals after the fit.

Solutions were studied which contained only F3-2 data but the six state parameters were highly correlated due to the poor geometry covered by this particular arc. As mentioned earlier the differencing destroys geocentric range-rate information leaving only the right ascension and declination of the spacecraft. As with classical astronomical observations, the restriction to angular measurement demands longer arcs or a better geometry to determine the orbit. Thus loosely weighted two-way doppler and ranging data were introduced to resolve this problem without excessively reintroducing process noise.

IX. Differenced Doppler, Two-way Doppler and Range

Once the geocentric information (F2 and Mu) is included, the indeterminacy of the orbit decreases. Although about half the correlations in spacecraft state are still above 0.9 when F2 and Mu data are included, the improved B-plane behavior gives us confidence that the problem is disappearing. There were other encouraging results as well. The estimated values of station location which are provided by the F2 and Mu data are about -4 m in longitude change and less than 2 m in spin axis change (Fig. 7). The estimated value of baseline longitude is also close to -4 m which is consistent with the change occurring at each station. However, the estimated value of the change of baseline projection Δr_b , which is about 12 m is larger than we expected. This could be due to the large *a priori* value used for r_b ($\sigma_{r_b} = 1$ km) and the relatively high correlations with those bias parameters ($\rho \approx 0.7$).

There was also good repeatability of the estimated values of frequency bias for solutions with different data weights and estimated parameters. The average magnitude of the estimated biases was about 4 mHz and they were slowly varying most of the time. This implies that the earlier variations were in fact due to absorption of process noise on a pass by pass bias.

B-plane solutions show significant improvement when the differenced data were tightly weighted (Fig. 10). Among the solutions, cases A, B, and C coincide with one another and cases E, F, and G do also. This indicates that the differenced data with F2 and Mu are not sensitive to solar pressure, attitude control, GM Moon, GM Mars and ephemerides, which is to be expected since they all affect the geocentric motion. It is only sensitive to station locations and baseline parameters.

X. Differenced Doppler and Two-way Doppler

Solutions with data weights: $\sigma F3-2 = 0.002$ Hz, $\sigma F2 = 0.011$ Hz, without Mu data were attempted but they moved the B-plane results further away from the CBE. The residuals induced in Mu were far too large, and the station location changes were unreasonable.

XI. Differenced Doppler and Range

A solution with data weights: $\sigma F3-2 = 0.002$ Hz, $\sigma Mu = 50$ m was tried. Similarly to the previous case the results moved the B-plane solutions further away from the CBE but in the opposite direction. The residuals induced in F2 were quite large. Station location changes were also unreasonable.

The last two solutions (F3-2 with F2 and F3-2 with Mu) indicate that the poor geometry seriously degrades the stability of the orbit determination, and it becomes necessary to include both geocentric range and range-rate information to obtain a correct solution.

XII. Conclusions and Recommendations

This demonstration shows that differencing two-way and three-way doppler data can reduce the effect of process noise in the spacecraft. However, referring to Fig. 11, it is not as clearly demonstrated as was hoped for. The F2-only solution using trajectory corrected for gas leakage performs almost as well as the solution using differenced data and a trajectory that ignores gas leakage. It is not clear from this demonstration whether F3 data without differencing can help the gas leakage problem, since no really good solution was obtained from this data type. However, this may be due to the pathological data arc which undermines attempts to remove the three-way frequency bias. It remains to be seen how effectively sequential filtering can employ three-way data, possibly without differencing, in a high process noise environment.

Future demonstrations of two-station tracking should be made over sufficiently long arcs, so that singularity between parameters can be more readily overcome. With a sufficiently long arc of data, the problem of solving for the three-way bias which beset this demonstration very likely could be handled. Even with hydrogen masers, the elimination of the three-way bias can be a significant problem. As previously noted, the two-way and three-way

solutions as well as differenced data solutions did not produce consistent values for these biases (Fig. 4). To obtain a consistent set of values for the three-way biases, it was necessary to weight the F2 data, corrupted by process noise, more heavily than was desirable. Future demonstrations should ensure that handovers of transmitter assignments be performed at the middle of the overlap when-

ever possible, since this greatly reduces the difficulty in solving for the three-way frequency bias.

In addition, the ODE should be modified, so that synchronization between two-way and three-way data can be obtained when compressions of these data types are performed.

Acknowledgments

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Reference

1. Ondrasik, V. J., and Rourke, K. H., "Applications of Quasi-VLBI Tracking Data Types to the Zero Declination and Process Noise Problems," paper presented at AAS/AIAA, Astrodynamics Specialties Conference, AAS No. 71-399, Aug. 17, 1971.

Table 1. Number of data points

Data type		DSS 12	DSS 41	Subtotal
F2	Truncated ^a F2	295	130	425
	Near meridian passage	130	63	193
F3		36	180	216
F3-2		35	170	205
Mu		14	0	14
Total		370	480	850

^aF2 data outside the common view periods were deleted.

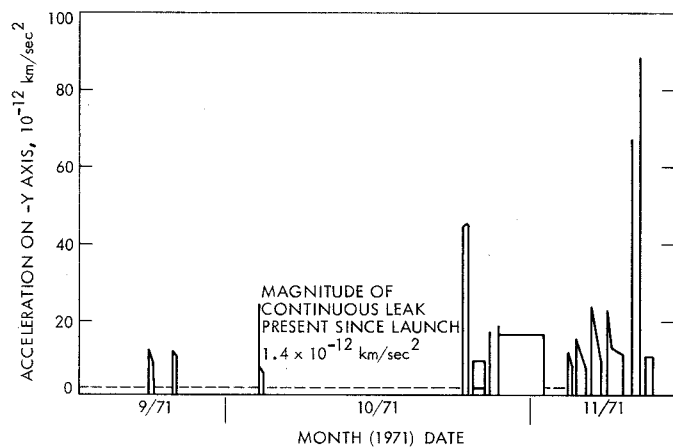


Fig. 1. Mariner Mars '71 spacecraft accelerations due to attitude-control gas leakage

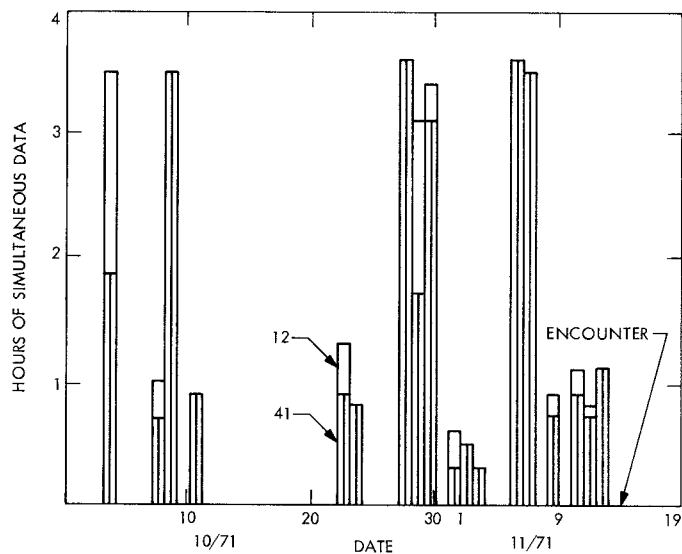


Fig. 2. Mariner 9 simultaneous doppler data (hydrogen masers)

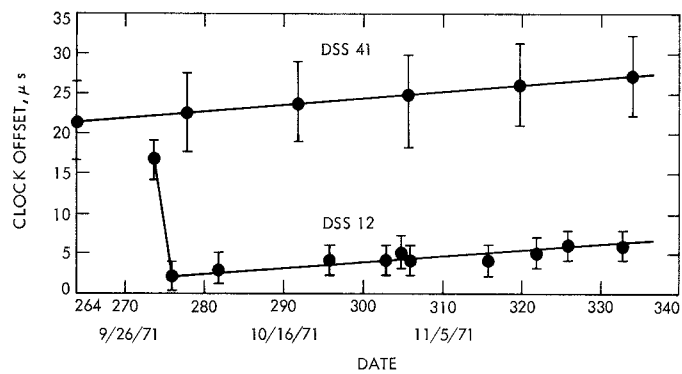


Fig. 3. DSSs 12 and 41 clock offsets

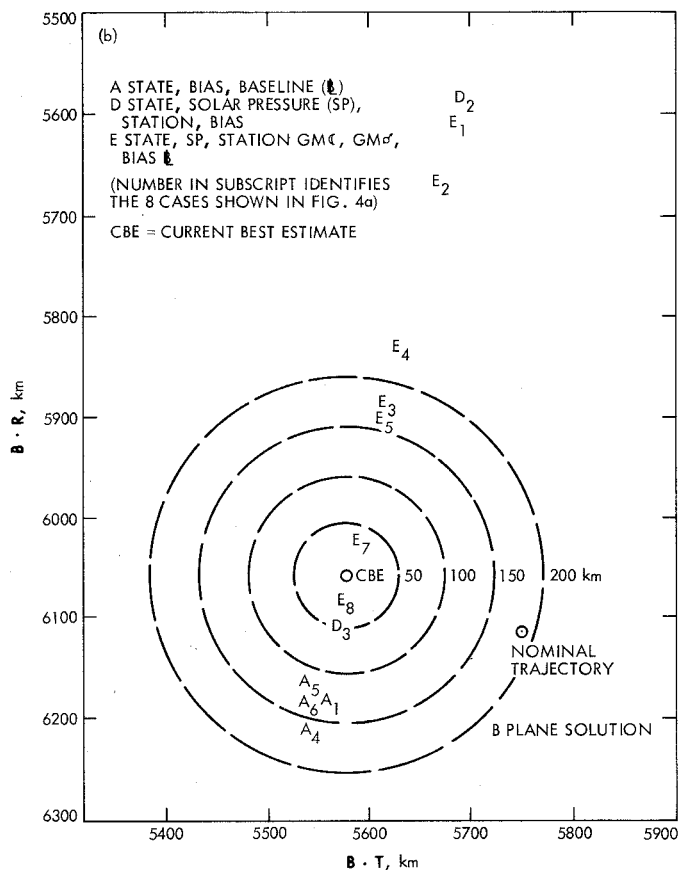
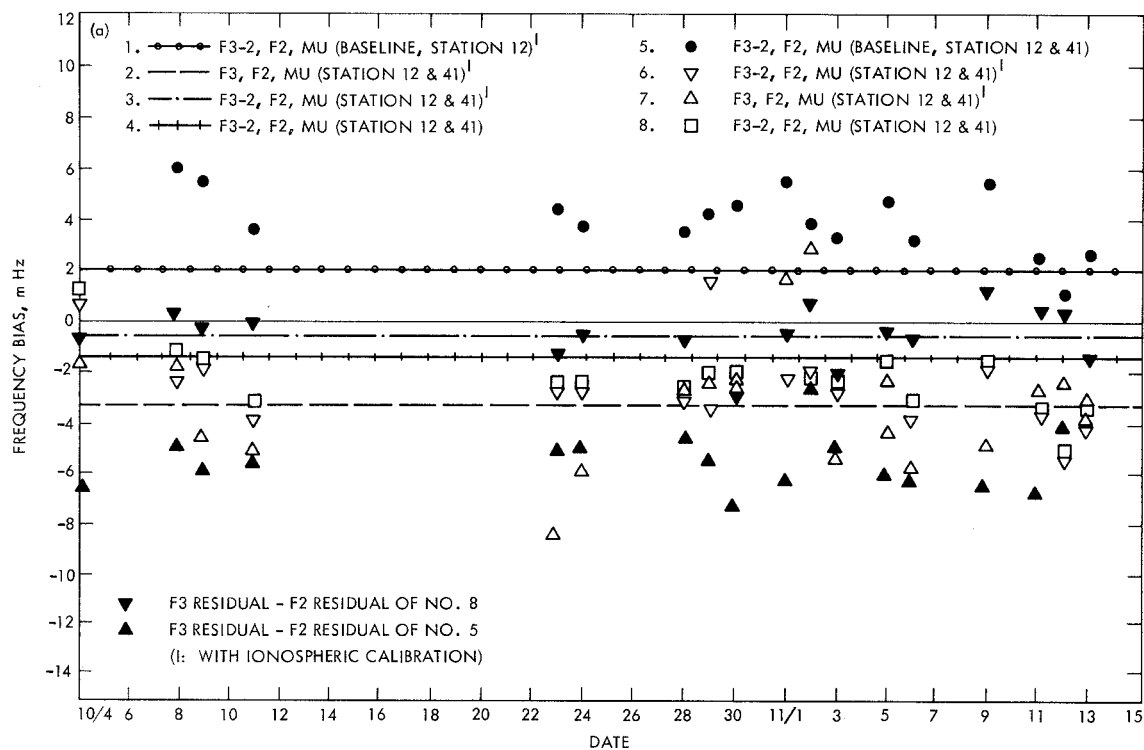


Fig. 4. Two-station doppler solutions: (a) Estimated frequency offset between two frequency standards, (b) target plane solutions

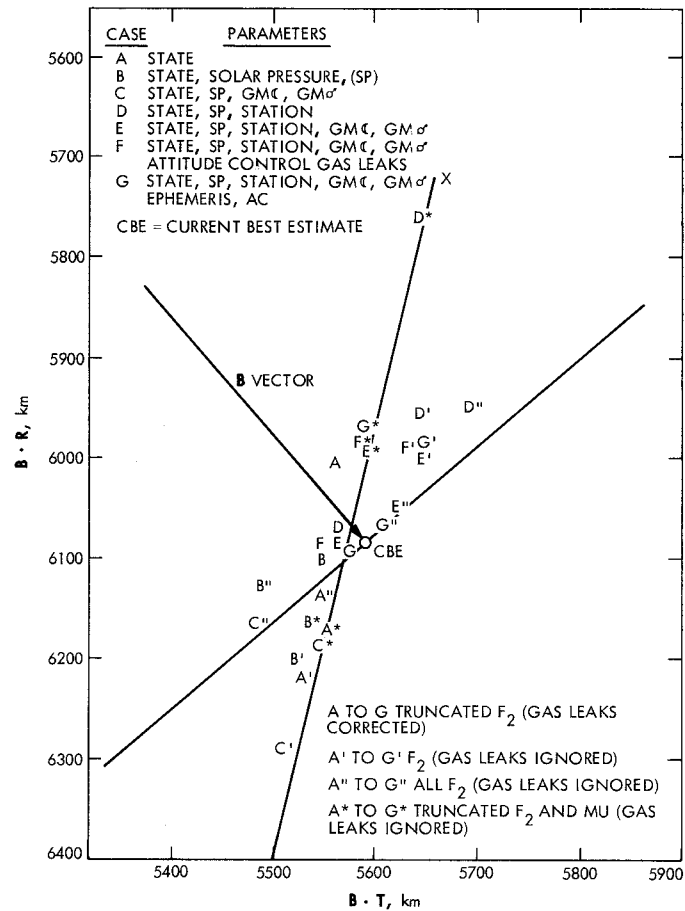
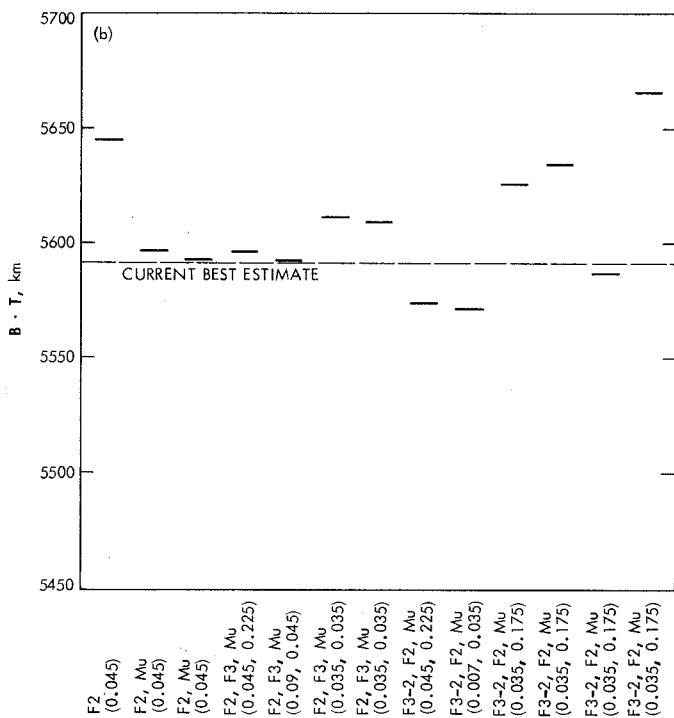
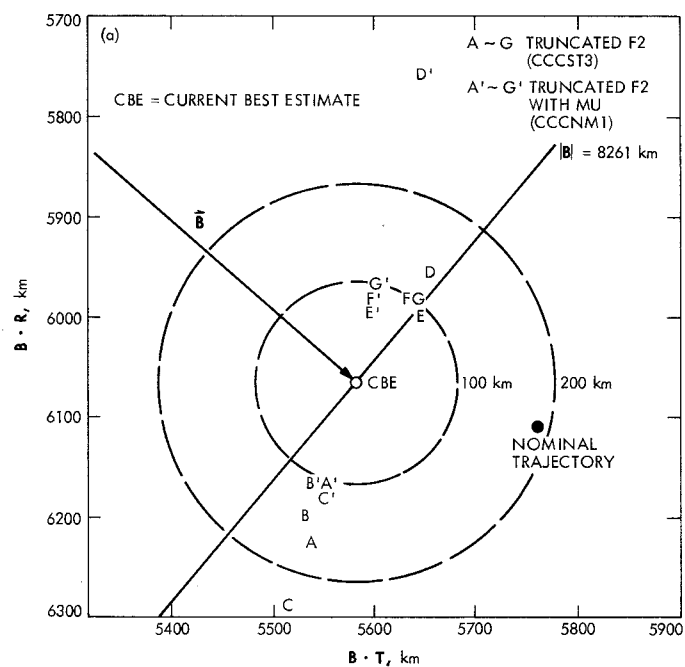


Fig. 5. Two-way doppler B-plane solutions



NOTE: DATA WEIGHTS IN PARENTHESES ARE IN Hz OR ns

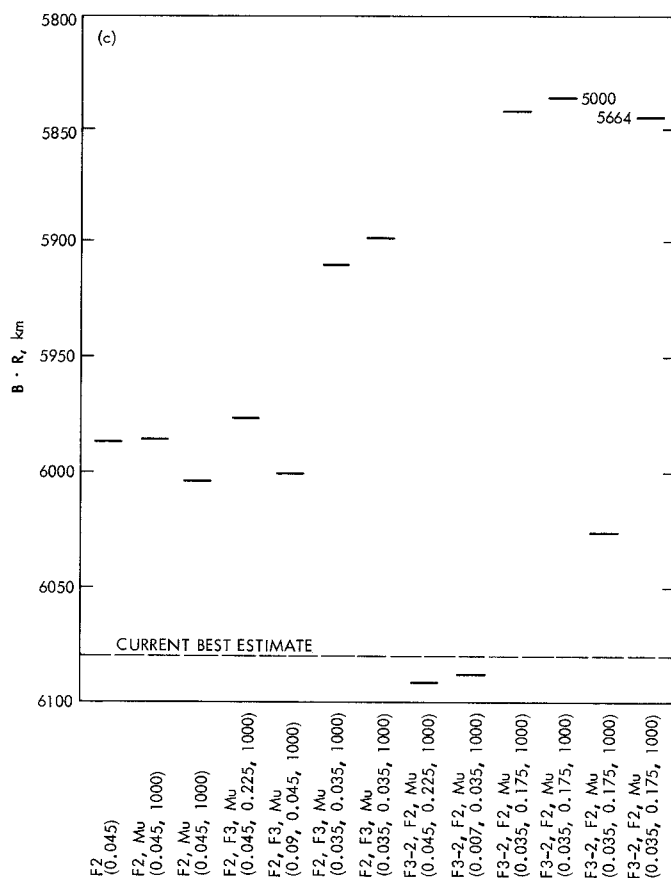
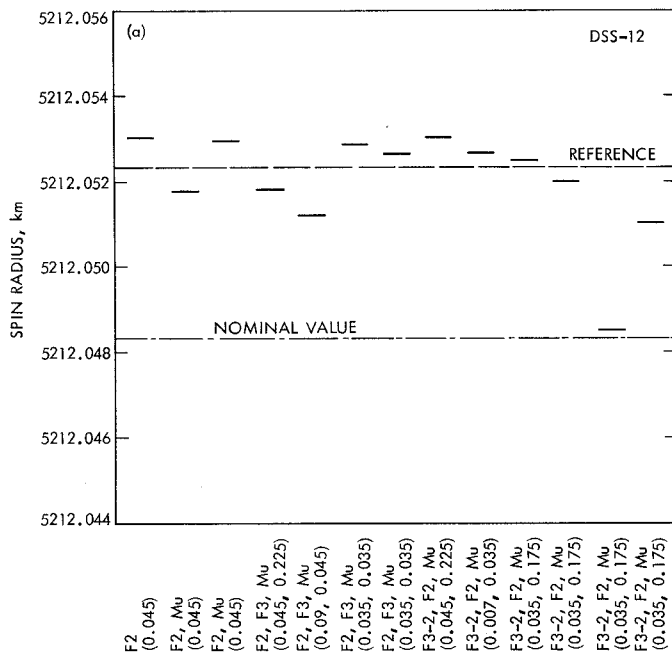


Fig. 6. Two-way doppler B-plane solutions: (a) target plane solutions, (b) $B \cdot T$ results, (c) $B \cdot R$ results



NOTE: DATA WEIGHTS IN PARENTHESES IN Hz OR ns

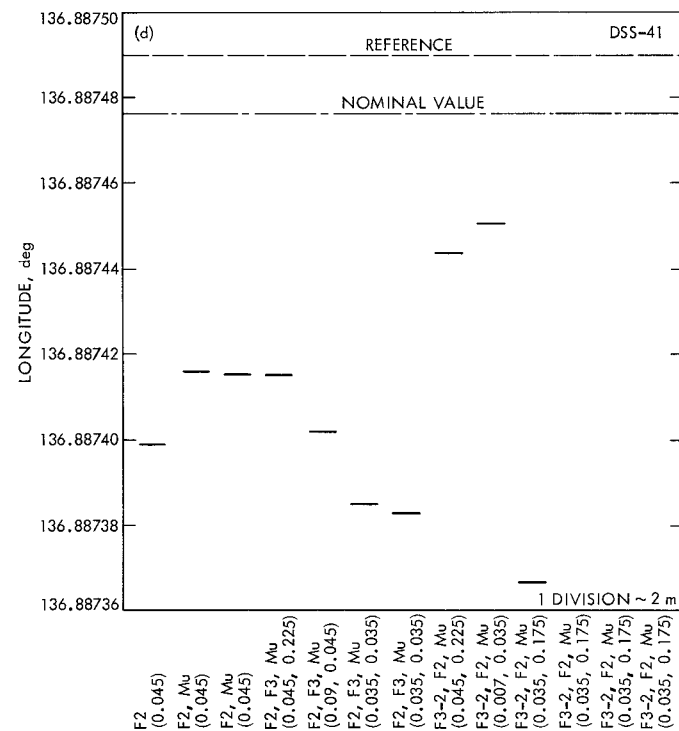
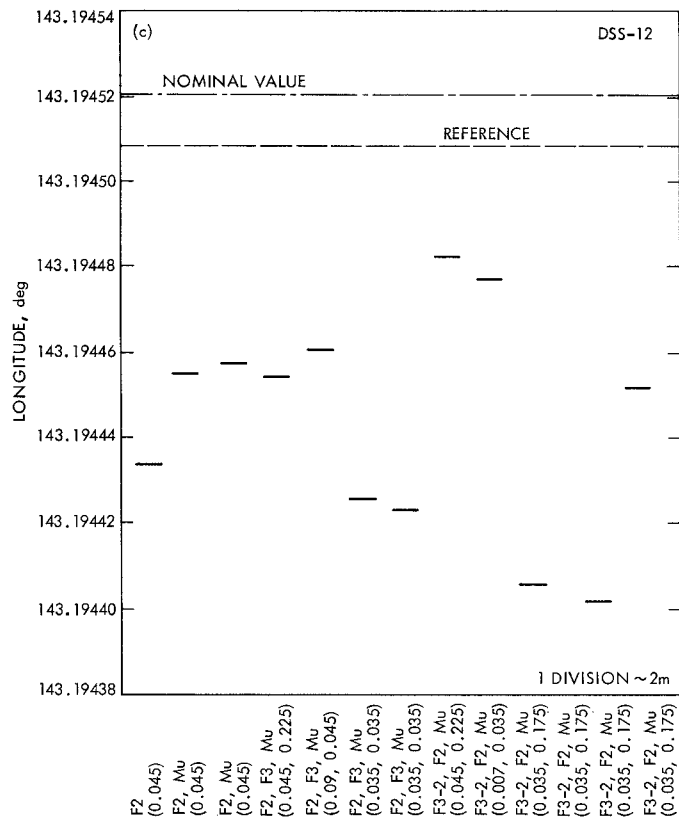
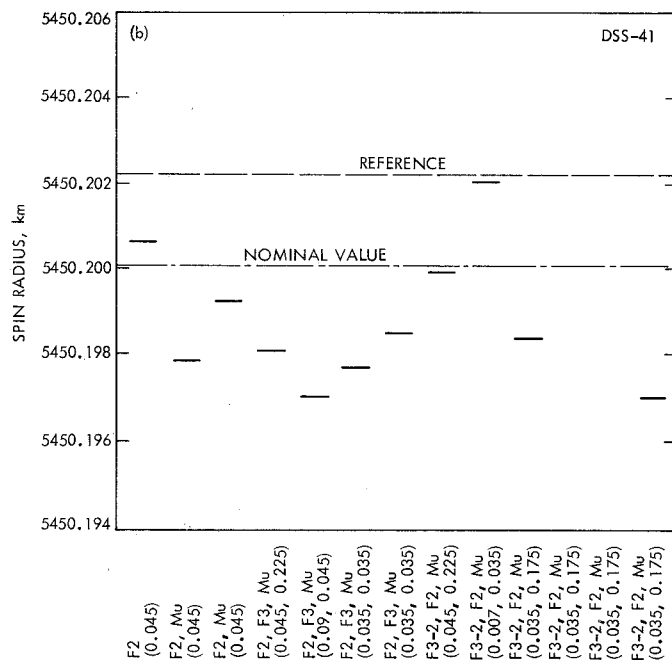


Fig. 7. Station location results: (a) distance off spin axis, DSS 12, (b) distance off spin axis, DSS 41, (c) geocentric longitude, DSS 12, (d) geocentric longitude, DSS 41

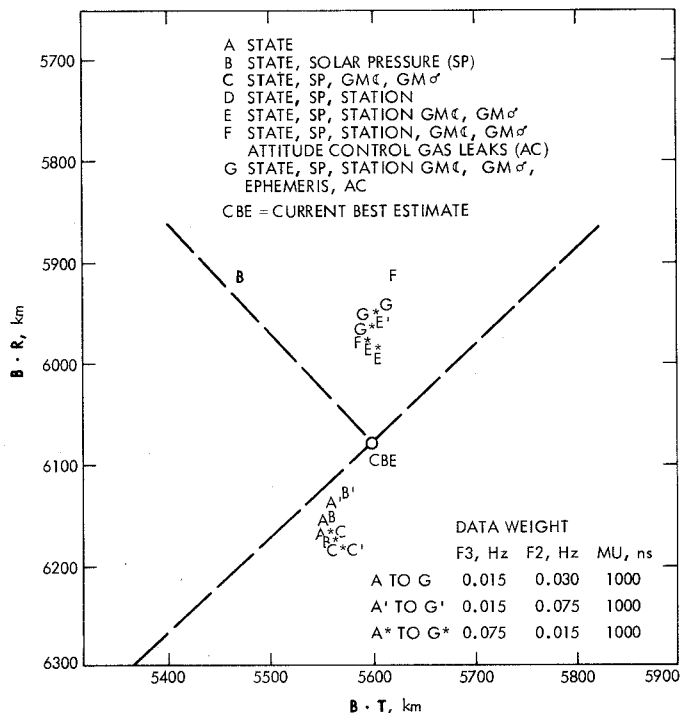


Fig. 8. Two-way and three-way doppler B-plane solutions

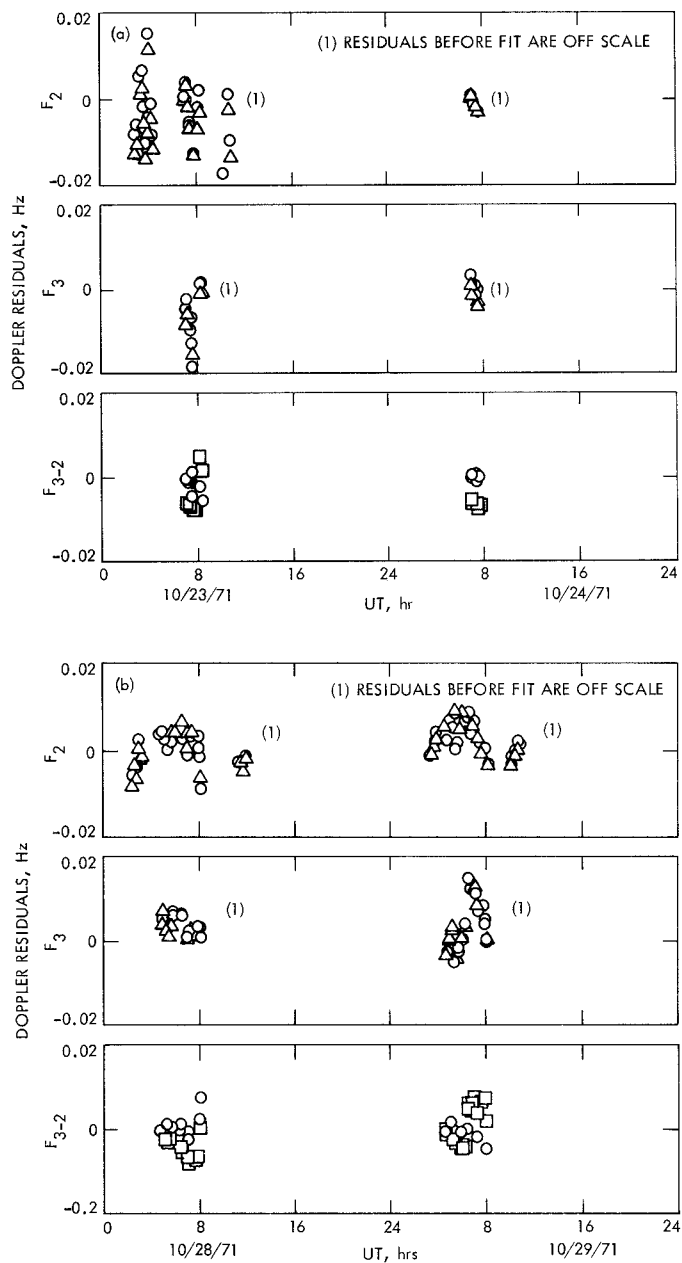
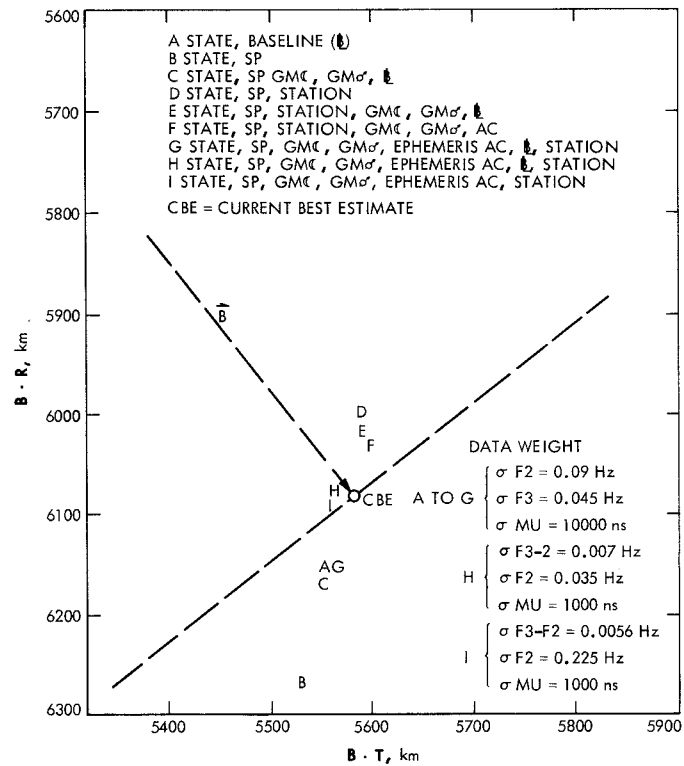
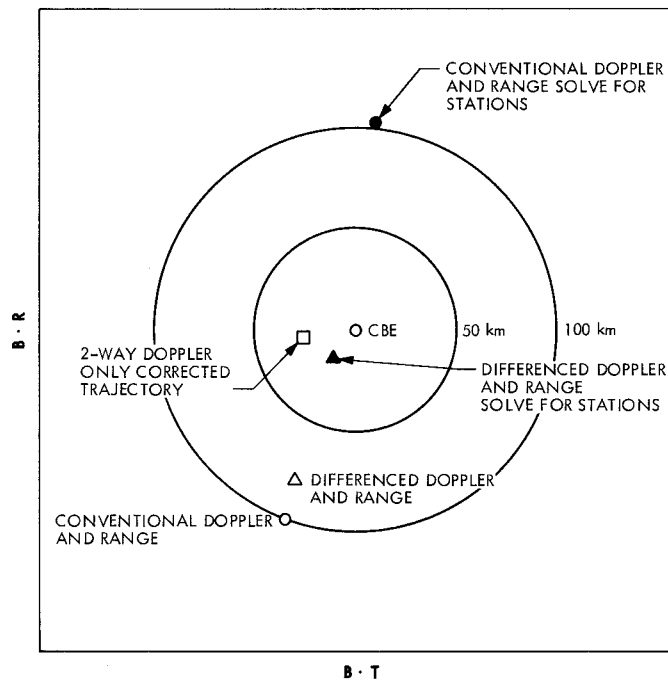


Fig. 9. Mariner 9 doppler residuals: (a) on October 23 and 24, 1971, (b) on October 28 and 29, 1971



**Fig. 10. Two-way and differenced doppler with range
B-plane solutions**



**Fig. 11. Summary of results from Mariner 9 two-station
doppler demonstration**